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Black carbon emissions and regulatory policies in transportation

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ABSTRACT

The paper assesses evidence concerning the effects of transportation's black carbon emissions on climate change, public health, and food production; and it discusses policy issues posed by the emissions. Black carbon emission mitigation policies at all levels offer significant potential climate, health, and food co-benefits, and they are attractive in terms of economic cost-effectiveness and political feasibility. The paper presents an analysis of regulatory issues in maritime shipping and aviation, which are increasingly salient, and which are largely independent of the revelations of "diesel gate" in the motor vehicle industry. Yet, there are linkages in the technological and policy issues of the motor vehicle industry and issues confronting maritime shipping and aviation. Black carbon emissions are among the core regulatory policy issues in all three industries, and they have not been adequately addressed by policymakers. The paper concludes with specific policy recommendations at all governance levels.

1. Introduction

The air pollution policy agenda in transportation includes a rich mixture of issues in the motor vehicle, maritime shipping and aviation sectors. A common feature among the sectors is that black carbon (BC) emissions are a hazard to public health; in addition, BC's contributions to global climate change and its damage to food production are increasingly salient. Despite common elements in BC problems across transportation sectors, there are significant differences in mitigation policy issues and options. An understanding of the policy issues and options requires a basic knowledge of key concepts and facts about black carbon, as presented in this brief introductory section.

A simple definition of BC is that it is carbon particulate matter less than 1.0 μm across ($PM_{1.0}$) – or about one-twentieth of the diameter of a human hair - resulting from the incomplete combustion of fossil fuels and bio mass. Black carbon, it should be noted, is *not* "carbon black," which is a manufactured product that is used, for instance, to strengthen and blacken tires.

There has been some confusion and controversy about the use of the term, *black carbon*, as discussed in Appendix A of this paper (Andreae and Gelenser, 2006). However, there is widespread acceptance of a definition from a landmark study (Bond et al., 2013: 5389) – namely that BC is "ambient aerosol material" which is …

… a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels. It is distinguishable from other forms of carbon and carbon compounds contained in atmospheric aerosol because it has a unique combination of the following physical properties:

1. It strongly absorbs visible light ….
2. It is refractory; … it retains its basic form at very high temperatures ….
3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol ….
4. It exists as an aggregate of small carbon spherules.

BC is commonly called "soot," though this shorthand expression is not correct because soot contains other elements in addition to BC. In particular, in the context of climate change issues, it is important to distinguish between black carbon and organic carbon, which are both present in soot. Whereas black carbon has a global warming effect, organic carbon has a cooling effect. Since they are co-pollutants in soot, the relative amounts of black carbon and organic carbon in the emissions of different sources are important.

There is a consistently large ratio of black carbon to organic carbon in *diesel engine emissions*, and those emissions are a major source of BC and a significant contributor to global warming (IPCC, 2013: 360–361; Ramanathan and Carmichael, 2008; Smith et al., 2009: Table 4.9; US EPA, 2017). Diesel engines' emissions in the motor vehicle and maritime shipping segments are therefore a central concern of the paper; since aviation fuel also releases BC emissions and diesel engines are present in airport ground equipment, that sector is included as well. Furthermore, much of the analysis also pertains implicitly to off-road vehicles such as in agriculture and construction, as well as diesel

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locomotives, diesel-powered materials-handling equipment, and diesel-powered electric generators.

Globally, transportation accounts for approximately 19 percent of BC emissions, and diesel engines contribute 90 percent of transportation's share (US EPA, 2017). The transportation sector in the United States is estimated to account for about 52 percent of US black carbon emissions, and diesel engines contribute about 90 percent of the transportation BC emissions. Whereas BC emissions are reported to be decreasing in the US and Europe - though there are reasons to doubt this, as we shall see below - they are increasing in much of the rest of the world. Although China's BC emissions have been rising, projections of future levels depict increases or decreases depending on implementation of emission reduction policies (UN Environment Program and World Meteorological Organization, 2015). The paper focuses on the emissions and policies of China, Europe and the US because of their shares of the global BC emissions. Collectively, they produce about one-half of global BC emissions from "constrained combustion" (as opposed to "open biomass burning"), with approximately 30% from China, 10% from Europe, and 8% from the US (UN Environment Programme and World Meteorological Organization, 2011: 46; also see Bond et al., 2013; Climate and Clean Air Coalition, 2018; UNEP, 2015). Of course, projections of future emission levels are the most policy relevant, and they are discussed in sections 2 and 3. The paper focuses on international policy issues and options, as well as key jurisdictions based on the level of their emissions and/or the developed state of their regulatory frameworks on black carbon emissions.

2. Black carbon emissions: effects and sources

2.1. Effects

A distinctive and significant feature of BC emissions is that their public health and food production effects are experienced directly at local and regional levels because they result in particulate matter depositions as well as atmospheric pollutants. Thus, in addition to its role as a *global* climate change forcing agent, BC is a *locally* and *regionally* significant air pollutant with public health and food production effects (CCAC, 2016; Pandis et al., 2014).

2.1.1. Public health

Much is known about the health effects of black carbon emissions on the basis of a large number of studies over several decades (Anenberg et al., 2011; Corbett, 2007; Janssen et al., 2012; Shindell et al., 2012a, 2012b; Smith and Haigler, 2008; Smith et al., 2009; WHO, 2012: vii). The health effects include premature deaths from lung cancer and cardiovascular problems, as well as lost work and health care costs from chronic and acute cases of asthma and other disorders. BC emissions worldwide cause on the order of millions of premature deaths per year (US EPA, 2012: 21). Of that total, hundreds of thousands of annual deaths in the EU-28 countries have been attributed to BC (European Environment Agency, 2017a,b), and 125,000 in the US (Bahner et al., nd). As for China, studies have focused more on the magnitudes of sources of BC emissions than their effects (Bond et al., 2013; Ni et al., 2014; Ramanathan and Carmichael, 2008); however, a study by Ding et al. (2016) found dangerously high levels of BC emissions in four Chinese mega cities, with clear but unquantified consequences for lung cancer and other sources of premature death. Although health studies of the effects of BC have typically been focused as a matter of metric convenience on particulate matter of 10 μm or less across, it is the smaller $PM_{1.0}$ BC particles, in particular, that are the principal cause of health problems. Volumes of BC emissions as $PM_{1.0}$ are strongly correlated with volumes of $PM_{2.5}$ and PM_{10} over time and across areas. BC's health effects are evident from studies of both short-term (daily) and longer-term variations in exposure levels.

Because of the localized and regionalized public health and food production impacts of BC emissions, they pose different challenges to policy making and economic theory, compared with long lived, globalized greenhouse gases (see Bennear and Stavins, 2007, for a theoretical discussion of such issues).

2.1.2. Climate change

As Yamineva and Romppanen (2017: 195) have noted, black carbon has not been so widely studied by climate scientists, nor as widely discussed by climate change policymakers, in comparison with carbon dioxide. This has been largely because black carbon is particulate matter, not a gas. As a result, the effects of BC have only relatively recently been getting extensive attention in the climate science literature. However, in the most extensive climate change study of black carbon available, Bond et al. (2013) conclude that BC's contribution to global warming is 55 percent of carbon dioxide's impact, and thus more than any of the other greenhouse gasses, including methane. Per tonne or other standardized unit, the global warming impact of black carbon is as much as thousands of times greater than carbon dioxide according to the 20-year Global Warming Potential (GWP) metric. See Appendix A for a more detailed and documented discussion of climate change metrics and definitional issues.

The warming effects of black carbon are especially problematic in the Arctic (AMAP, 2011, 2015; Brewer, 2015; Brewer, 2019; Comer et al., 2017; Eleftheriadis et al., 2009; Flanner et al., 2007; Hegg et al., 2009; Romppanen, 2018; McConnell et al., 2007; Sharma et al., 2006; Yamineva and Kulovesi, 2018; also see for other regions Reddy and Boucher, 2007; Rypdal et al., 2009). Additional measurement and policy issues are discussed in sections 3 and 4, Appendix A and subsection 2.2.2 below.

2.1.3. Food production

Studies of the food production consequences of BC emissions have been less extensive, but results to date indicate that BC reduces the yields of many crops. For instance, the crop yield loss specifically from BC emissions worldwide for four crops – maize, rice, soybeans and wheat – could be reduced by 24 million tonnes per year through technological measures and by 2 million tonnes by regulatory measures, according to estimates by Shindell et al. (2012a,b: 186, Table 2) using empirically-based modeling exercises. The reductions would be the greatest (in absolute amounts) in China, India, US, Pakistan and Brazil.

2.2. Transportation sector sources

Measuring and projecting transportation sector emissions of BC are particularly challenging because of the distinctive sets of analytic issues associated with individual industries. For the motor vehicle industry, among the most salient issues are the manipulations of official emissions testing by automotive manufacturers in the US and Europe, which have led to significant under-reporting of emissions. In maritime shipping, estimates based on fuel sales underestimate BC emissions. Conventional aviation measures based on a "smoke number" also underestimate BC emissions. Details for the sectors follow.

2.2.1. Motor vehicles

In the motor vehicle industry, there are continuing questions about the accuracy of the actual levels of BC and other emissions compared with the reported emissions from tests in the US and EU. Though there have been acknowledged underestimates as a result of some firms' practices, how big the required corrections are for aggregated US and EU estimates is still being investigated. (See Resitoglu et al., 2015; for information about vehicle emissions and control technologies.)

Emission testing controversies for the motor vehicle industry in the US and in Europe have of course attracted much attention to emissions standards and testing procedures. While the controversy in the US has been focused on the test-defeating equipment of a particular manufacturer, in the EU the controversy has been more broadly concerned

with industry-wide standards and test procedures. The standards adopted by the European Commission under pressure from the industry are higher than originally intended by the Commission; and the tests, which are conducted by firms selected and paid by the auto manufacturing firms not by the Commission or independent third parties, are not subjected to rigorous quality control procedures.

2.2.2. Maritime shipping

IMO estimates of BC emissions in the maritime shipping industry have been found to be underestimating actual levels. Wang and Minjares (2013) computed global estimates for 2007 that were 42 percent higher than IMO estimates, and Arctic region estimates for 2004 that were 90 percent higher than IMO estimates. Insufficient data and modeling about BC emissions and depositions in the Arctic have led to underestimates of the role of BC from all sources in Arctic sea ice melt and land ice melt in the Arctic region (Brewer, 2019; also see AMAP, 2011, 2015). Corbett and Winebrake (2008: 18) found that marine fuel sales statistics have led to underestimates of marine energy use by a factor of two, and they therefore also lead to underestimates of BC emissions. An assessment of measurement methods for BC maritime shipping emissions is underway by ICCT (2017a) for the IMO. (For discussions of climate change issues at the IMO and in the maritime shipping industry more generally, see Bows-Larkin, 2015; Asariotis and Benamara, 2012; Azzara and Rutherford, 2009, 2015; US EPA, 2015).

The amounts of vessel traffic and their loads have been strongly correlated with GDP at the global and national levels (Corbett and Winebrake, 2008: 7–9). Maritime shipping's BC emissions have been forecast to approximately triple by 2050 versus 2004, despite IMO fuel efficiency regulations (Corbett et al., 2010; Azzara et al., 2015).

2.2.3. Aviation

The “smoke number” - which is a commonly-used metric for emissions in the aviation industry - only indirectly estimates the mass of BC emissions by optically measuring the visibility of the plume of an aircraft during cruise speed as well as take-off and landing. The smoke number, therefore, is not a direct chemical measurement, and studies have found that the smoke number underestimates emissions levels. One study (Stettler et al., 2013) found that the smoke number underestimates BC emissions by a factor of 2.5–3. A study by Stettler et al. (2011) found that the estimate of global aviation BC emissions should be about 3 times greater than earlier estimates. Another report of UK airports representing 95 percent of UK passenger traffic in 2005 by Stettler et al. (2013) also found greater BC emissions than those in studies using the smoke number; in fact, more direct alternative measurement methods found BC emissions to be 8 times greater than smoke number studies. In sum, these studies indicate that aviation's BC emissions estimates based on smoke numbers are 2.5–8 times too low.

Aviation traffic volumes are expected to increase for at least the next few decades, as they have for the past several decades, typically by more than the rate of increase in world GDP. Forecasts by ICAO (2016a: 10, 23; also see, Bows-Larkin, 2015) are that total world passenger traffic will increase by an average of 4.6 percent per year over the 20 year period from 2012 to 2032 and 4.5 percent over the 30 years from 2012 to 2042. These forecasts compare with 5.2 percent per year on average that was experienced from 1995 to 2012. The parallel forecasts for freight traffic are averages of 4.6 percent and 4.5 percent per year.

A study at the MIT Joint Program on Science and Policy conducted an extensive modeling exercise of future global aviation emissions, including BC emissions. They found BC levels of emissions in 2050 that were 1.38–4.87 times greater than 2006 levels (Brasseur et al., 2016: 567, Table 2).

3. Policies

Fig. 1 provides an overview of policy issues in terms of three industry sectors and four levels of governance. The discussion below highlights many of these illustrative issues.

3.1. Motor vehicles

Partly in response to revelations of inadequate test procedures and cheating by manufacturers – commonly known as "dieselgate" - and partly as a result of increasing awareness of air quality and associated health problems, many European cities have begun to limit diesel vehicles (Tietge and Díaz, 2017). The cities of Athens, Madrid, and Paris plan to ban diesel cars and delivery vans by 2025, and other cities are considering such measures. Barcelona, Berlin, Cologne, Munich and Stuttgart are putting in place restrictions or considering them. In February of 2018, a German court ruled that cities could and should impose legally binding limits on diesel-powered motor vehicles (Wacket and Wissenbach, 2018).

Norway has established a national target of eliminating all new fossil-fuel cars by 2025; current policies include tax incentives, preferred access to municipal parking facilities, and waivers of fees for ferries and toll roads (Vaughn, 2017). As of the first two months of 2017 in Norway, there were more new EVs and hybrid cars purchased than new fossil fuel cars (Forrest, 2017).

Mexico has also decided to ban diesel vehicles, and it has included reductions of black carbon emissions in its Paris Agreement list of Nationally Determined Contributions (Mexico, 2019) with an expectation of reducing BC emissions by 51%.

At the regional level, the EU is considering reforms of motor vehicle emissions standards and testing procedures in response to deficiencies in the current system. The second largest auto manufacturer in Europe - PSA, which makes Peugeots, Citroens, and other brands – now publishes *on-road* fuel consumption data for 30 models of cars, which are consistently higher than conventional off-road tests (Transport and Environment, 2016).

Moreover, *implementation* of motor vehicle emission standards policies in the EU remains a problem – at the EU level and at the national level (Yamineva and Romppanen, 2017). Thus, there is an on-going, widening controversy about the “gaming” of new EU emission limits based on percentage reductions beginning in 2020, with actual emissions during the immediately preceding years serving as a base for the computation of the percentage reductions. The base is being *increased intentionally but legally* by auto firms because the new limits are expressed in percentage reduction terms, not in absolute amounts. Of course, European regulations of automobile emissions have not been the only ones that have been thwarted by manufacturers; so have heavy trucks.

Heavy duty diesel truck manufacturers have been on the defensive on two policy fronts. One concerns the use of methodologically flawed reports of purported improved fuel efficiency – claims of 30 percent over 1965–2010 and 60 percent over 1975–2014. These compare with the results of a more methodologically robust study (Muncrief, 2017) covering 2002–2014 trucks by six major European manufacturers, which found no significant change in fuel efficiency performance. Developments on the other policy front concern compliance with EU competition policy law. The largest competition policy fine in EU history - 2.93 billion euros, or about 3.28 billion US dollars - was imposed on the basis of five firms colluding in a cartel over 14 years, including “coordination on timing and coordination on passing on of costs of emission technologies for trucks compliant with newly introduced emissions standards” (European Commission, 2016a).

US regulations of diesel trucks continue to pose unresolved issues. The current administration announced it would reverse the previous administration's position, and not restrict the use of old diesel engines, which are major emitters of BC, in replacements of accident-damaged truck "gliders" (i.e. the front of the truck). Many law suits were filed on the grounds that the change was illegal, and a federal judge put an immediate "stay" on the policy change. When the US EPA Administrator was subsequently forced out of office for other reasons, his replacement

Governance Levels	Motor Vehicles	Maritime Shipping	Aviation
Global	UNFCCC, international transfers of diesel particulate filters	IMO, fuel sulfur content IMO, greenhouse gas limits	ICAO, emission offsets
Regional	EU, emission testing standards and implementation practices	North America and Europe, coastal Emission Control Areas	EU, inclusion of aviation in ETS
National	US, national policy reversals in fuel efficiency and other regulations	China, coastal Emission Control Zones	UK, France and other countries, airport expansion plans
Local	Cities in Germany, UK and other countries, regulations on vehicle travel into urban areas	Local authorities in Canada, US, Netherlands and other countries, seaport regulations on ship emissions	Restrictions on airport operations and/or expansions

Fig. 1. Overview of illustrative policy issues according to governance levels and industry sectors.

restored the previous policy – but not permanently.

US regulations concerning motor vehicles more generally were experiencing an unprecedented degree of uncertainty as of the end of 2018, when the Trump administration attempted to reverse Obama administration regulations including fuel efficiency regulations, but encountered numerous legal cases intended to prevent the implementation of new policies. The future of US national regulations was thus being determined, to a great extent, in federal courts around the country.

3.2. Maritime shipping

There are developments concerning shipping's emissions at many levels of government (UNCTAD, 2016). The targeted emissions in some cases include diesel emissions and thus black carbon. In other cases, the explicit target is increased fuel efficiency that would reduce emissions, including black carbon emissions. A limitation of fuel efficiency measures of course is that the increases in efficiency must more than offset increases in volumes of traffic. This is a problem in maritime shipping, as it is in aviation.

At the local level, in North America four Pacific coast cities - Los Angeles, Long Beach, Oakland and Vancouver - have all adopted policies that reduce BC emissions. Los Angeles and Long Beach together reduced particulate matter emissions, including black carbon, by 81 percent as of 2013 compared with 2005. An interesting feature of their program is to use positive incentives in the form of cash payments for each vessel entering the ports that meets voluntary emission standards – as opposed to negative penalties for non-compliance with mandatory limits.

In Europe, Gothenburg and Rotterdam are in the process of implementing regulations on ships in their ports. At the regional EU level, the situation is more complex. There is support in the Commission and in the Parliament to put the International Maritime Organization (IMO) on notice that the EU will include shipping in its Emission Trading System starting in 2023, unless the IMO agrees to a global system that would reduce shipping's emissions. The EU proposal is pending approval by its national member governments, who are divided. In any case, new EU regulations entered into effect on January 1, 2018, that require ports to collect data on ships' emissions, and this is intended to be the beginning of a series of regulations to be imposed over the next several years (European Commission, 2016b).

In Asia, important policy issues concern major long-term seaport expansion plans in India and China. India has plans to develop ten new mega-ports and upgrade 12 existing government-owned ports; in addition, private developers have plans to create new private ports.

As for China, about two-thirds of the world's 50 largest container ports are wholly-owned or partly-owned by Chinese investors. Its Maritime Silk Road (MSR) plan includes about six ports in China and another 15 or so in other countries, including seven in Africa and four in Europe. Some have already been built, others are in advanced construction stages, yet others are being planned. As many as 73 countries have signed up to be included in the MSR.

Given the numbers and sizes of these Indian and Chinese projects, emission control policies at their facilities will affect regional and even global BC emission levels, as well as local emissions of course. To the extent that Chinese MSR port projects in foreign countries will be subject to local policies, this would mean for instance being subject to EU as well as local and national policies in Athens and Venice.

International regional Emission Control Areas (ECAs) have been established in North American waters and Northern European waters, and national Chinese Emission Control Zones (ECZs) are under development in China. The North American ECAs have been estimated to prevent a tripling of $PM_{2.5}$ by 2030, mostly through fuel-switching (US EPA, 2010). There is a proposal for a regional agreement for the Arctic that is specifically focused on black carbon (Brewer, 2015, 2016; also see Romppanen, 2018). It could be modeled in some respects on the existing ECAs, or perhaps attached to one of them as an extension.

In terms of global-scale regulation in maritime shipping, the International Maritime Organization (IMO) is the designated international institution, as a UN Specialized Agency in general for international maritime issues and as designated by the UNFCCC process to be the climate change agency for international maritime shipping. (See Chircop, 2016, for the legal history of climate change issues at the IMO.) The most relevant IMO activities concerning black carbon emissions have followed two tracks. One is the fuel efficiency track, which has promulgated mandatory regulations concerning vessel

design and operations, with different phase-in periods for new and existing vessels (IMO, 2017). The other focuses on black carbon emissions; thus far, the IMO has accepted the *definition* in Bond et al. (2013), as mentioned in the introduction of the present paper. It has also been developing a *protocol for reporting* black carbon emissions (IMO, 2012; Kopela, 2017), which is still being considered. There is also an on-going process to assess BC *emissions measurement methods* for the benefit of the IMO by the ICCT (2017b). At the IMO, in April 2018, an agreement on an "initial strategy" for reducing greenhouse gasses does not include black carbon. (For summaries of the agreement, see IMO, 2018; Rutherford and Comer, 2018; Brewer, 2018.)

There have been some private initiatives to make greater progress in regulating marine emissions (Kopela, 2017). These include the Sustainable Shipping Initiative, the Clean Shipping Index, and the World Ports Climate Initiative of the International Association of Ports and Harbors (IHPH). The latter in particular has included ships' black carbon among its concerns – along with the diesel engine black carbon emissions of motor vehicles, trains and equipment in the harbor areas (see Brewer, in progress).

3.3. Aviation

Air quality policies concerning aviation are fundamentally different from those for motor vehicles or maritime shipping because diesel engines are not used in aircraft, though they are used in ground services equipment. Nevertheless, there are significant black carbon emissions from aircraft, and traditional measurement methods underestimate the volume of black carbon emissions from aviation fuel (as noted above in section 2.2.3).

Multiple types of policies affecting aviation are at issue at multiple levels of government (OECD, 2012). Many kinds of policies can limit BC emissions: limitations on the number of flights, changes in air routing and traffic control, increases in fuel efficiency, adoption of alternative fuels, and more. Initiatives to reduce carbon emissions from the aviation industry have been especially numerous in Europe. The initiatives implicitly include BC, though they tend to focus explicitly on carbon dioxide. Policies have been evolving at both the regional EU level and at the national level, with local level issues and impacts in all cases.

There are evolving cases in which the specific issue is whether there will be restrictions - including perhaps prohibitions - of airport expansions, including the addition of runways. London's Heathrow airport is the best-known case, with the plans for its expansion still not entirely resolved at the end of 2018. The national UK government made a preliminary decision in October 2016 to approve a third runway, after many years of considering it. However, there are unresolved issues that could delay or prevent the final approval. One is that there are objections to deficiencies in the limitations on carbon emissions of flights using the new runway. The government's response has been to plan emission offset requirements and peat bog restorations in compensation. Second, because of the projected increase in emissions at Heathrow, there may be a need to reduce emissions in other sectors in order for the UK to meet its COP21 Paris agreement targets. Finally, there is an issue of whether other London area airports would have limitations on planned expansions and emissions.

Airport expansion plans in other countries are also in doubt. In Austria a national court has ruled that the planned expansion of the Vienna airport cannot proceed because it would violate Austria's emission targets, but the decision is being appealed. Plans and potential court cases are not so advanced in other countries; however, there are doubts about the fates in Germany for airport expansions at Dusseldorf and Munich, and in Ireland for Dublin. In France, President Macron cancelled further planning for an expansion of the Nantes airport after many years of locally-driven promotion of the project.

At the regional level, EU policy reflects the basic distinction between intra-EU flights versus flights that are entering the EU from non-EU countries or departing to non-EU countries. Flights involving non-EU countries account for about three times the volume of emissions from intra-EU flights. The current EU policy is to include only intra-EU flights in the European Emission Trading System (ETS). Extra-EU flights have been excluded from the ETS, at least until an agreed International Civil Aviation Organization (ICAO) system enters into operation in 2021. Because emissions from domestic aviation are included in the UNFCCC, parties to the UNFCCC can reduce emissions from these sources in the context of their Nationally Determined Contributions (NDCs) under the Paris Agreement.

The ICAO system – known as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) - will be voluntary initially and not become mandatory until 2028 (ICAO, 2016b). Even then, the ICAO system will not reduce the industries' emissions below business-as-usual projections (Rutherford, 2016). Whether the EU will include extra-EU flights in the ETS at some point during the 2021–2028 period, or after, obviously remains to be seen. In any case, CORSIA does not explicitly include black carbon emissions. Black carbon emissions were briefly mentioned in an ICAO Environmental Report (ICAO, 2010: 38–42) but without a substantive discussion of the issues, and they have not explicitly been on the ICAO agenda. Yet, in 2004, ICAO had adopted a goal that is potentially relevant to black carbon emission reductions – i.e. to "limit or reduce the impact of aviation emissions on local air quality" (ICAO, 2016a, 2017).

4. Policy implications

4.1. Geography: local, national, regional and global effects

The geographic scope of the impact of BC emissions is a combination of local, national, regional and global. The public health effects are localized, and they tend to be especially strong in large, densely populated urban areas with high volumes of motor vehicle, shipping and aviation traffic. Because of the projections of continued significant population growth in major urban centers, including many with seaports and airports, the development of local emission mitigation action plans should be a high priority. They offer quick health benefits and longer-term climate benefits as well. Food production effects are more regionalized, including in coastal areas along shipping routes. As shipping volumes continue to increase, food production in coastal areas along major national and international shipping lanes will obviously become more vulnerable to BC emissions.

The climate change impacts of BC emissions are more nearly globalized, though concentrated more in the northern hemisphere than southern hemisphere, and especially significant in the Arctic region (albeit with global consequences). The continuing and increasingly rapid rate of sea ice melt in the Arctic has already led to the development of long-term plans by China and South Korea to establish new routes through the Arctic region for shipments to European ports.

4.2. Industry sectors

As noted above, there are significant differences among the three transport industries in the sources of their black carbon emissions: diesel engines are the primary source of BC emissions in motor vehicles and in maritime shipping but not aviation.

As for technological solutions, diesel particulate filters (DPFs) have been widely used in the motor vehicle industry for decades and found to be cost-effective, including in their reduction of pre-mature deaths and other health problems. In maritime shipping, although there is on-going research into the potential of DPFs to reduce BC emissions, there is not yet a significant uptake of that technology.

Similarly, for alternative fuels there are significant differences among the three industries. For instance, liquefied natural gas (LNG) has already been utilized in some instances in maritime shipping, especially for ferries, and it could become more widespread for large LNG transport vessels, which can use a portion of their cargo for their

own propulsion (Thompson et al., 2015). The Russian government is especially active in developing this alternative. Yet, full cycle analyses suggest that the net impact of LNG is not climate friendly. There has also been some uptake of liquefied gasses in motor vehicles, busses in particular. In aviation, there has been interest and experimentation with bio-fuels, but with mixed results and doubts about the feasibility and cost-effectiveness of large-scale use of aviation bio-fuels.

The institutionalized policy regimes concerning BC emissions among the three industries are also substantially different. Motor vehicle emission regulations are overwhelmingly national (in combination with regional rules in the European Union), and they are thus highly variable internationally. Maritime shipping emission regulations, in contrast, have been developed at the global level within the IMO and to some extent at the regional level by small groups of countries. The international rules, however, are enforced at the local level by individual ports - some of them under the guidance of national authorities, depending on the nature of the national political system and legal relations among national, local and regional authorities. As for aviation, The Carbon Offsetting and Reduction Scheme, which ICAO has adopted, does not include BC emissions.

4.3. Policy options

In the context of such institutional and policy diversity, a wide range of specific policy options should be addressed.

- At the global level, mitigating BC emissions should become an urgent objective in ICAO and IMO. Although the IMO, as noted above, has a BC policy development process in place, ICAO does not. The IMO's April 2018 approval of an “Initial Strategy” to reduce greenhouse gas emissions is an important decision in a progressive direction to address climate change issues; however, its development of new measures to address black carbon emissions has been slow and lagging behind its concern with carbon dioxide emissions. Both are obviously important and require action.
- Also at the global level, technology transfer issues, including transfers of diesel particulate filter technologies in motor vehicles and shipping, should be included on the agenda of the Technology Mechanism of the UNFCCC.
- Annual COP meetings and other activities of the UNFCCC should expand recognition that domestic BC mitigation measures can be included in countries' Nationally Determined Contributions.
- At the regional level, all maritime shipping Emission Control Areas (ECAs) should include BC emission limits.
- Also at the regional level, an Arctic Black Carbon Agreement in the form of a “carbon club” should be negotiated. Joining such a “club” can be voluntary, but those who join must comply with binding obligations or face enforcement actions such as paying a fine, being denied access to club benefits, or being expelled. More generally, the issue of whether legally binding regulations or voluntary agreements are more effective or otherwise preferable is an important topic for further research.
- At the national level and in the EU, reforms of motor vehicle emissions standards and testing procedures should continue, and administrative and legal proceedings against offending motor vehicle manufacturers should of course be used to impose penalties on the offenders.
- At the local level, BC emission reduction strategies should be adopted, especially in large cities with seaports and airports. These programs should encompass all diesel engine sources of BC in shipping and aviation port infrastructure areas, including off-road vehicles, loading/unloading equipment, and diesel locomotives as well as on-road motor vehicles.
- Local-level undertakings to reduce BC emissions from motor vehicles should proceed according to local needs.

Such wide-ranging agendas should involve the participation of industries, governments, non-governmental organizations, international agencies and of course scholars. The payoff for the efforts could be cost-effective measures that can save millions of lives within a few years and many millions more within decades from a combination of their public health, food production and climate change benefits.

In short, a multi-technology, multi-policy, multi-governance-level approach that captures multiple benefits should be pursued. Such an approach should be responsive to the following key features of the political, economic and institutional contexts in which the policies will be considered:

Because black carbon is short lived particulate matter with public health and food production consequences at local and regional levels as well as climate change consequences at the global level, its political and economic implications are fundamentally different from greenhouse gasses. *The sources as well as the economic costs* of black carbon emissions are evident locally and regionally, and there are consequent political pressures at the local and regional levels – in addition to whatever global economic and political consequences there may be. Action on mitigation options focused at the local and regional levels are therefore more likely than global action options to be welcomed by publics and political leaders.

The institutional context for mitigating black carbon emissions from transportation is already highly pluralistic at the local, regional and global levels. There are some linkages and coordination mechanisms among governance levels; based on IMO agreements, for instance; local port authorities enforce some IMO regulations, and regional Emission Control Areas are recognized by the IMO as legally binding. At the same time, there are many ways in which local and regional governmental authorities have acted independently of IMO regulations. A major challenge of future policymaking will thus be integrating new regulations into the multi-level governance structure. This will be true not only of maritime shipping but also aviation and to a less extent motor vehicles. These and other inter-industry differences are reflections of the differences in their stakeholders.

There are of course enormous differences in the economic interests, political influence and corporate cultures among transport industry sectors. Aviation is still a relatively concentrated industry, as a result of mergers and strategic alliances, despite occasional new entrants. A small number of airlines and their home governments have thus been able to prevent black carbon emissions from being active issues on the ICAO agenda. Shipping is less concentrated, though competition is limited on some routes, as a result of strategic alliances. Yet, the container segment of the industry is dominated by a small number of firms that happen to have home countries with traditions of being environmentally sensitive and active on climate change issues in particular; and they have been able to lead the IMO to address climate issues in progressive directions. The motor vehicle industry, meanwhile, continues to struggle with the aftermath of the testing scandals in Europe and the US, with no end yet in sight. The patterns of industry and governmental stakeholders are likely to be powerful forces that facilitate - or hinder - efforts to limit black carbon emissions, with each sector doing so in its own distinctive fashion.

One implication of the inter-industry differences in the patterns of industry and governmental interests and influence is that the important issue of whether emission limitations should be binding or voluntary also varies across industries. Among the three transportation sectors in this article, binding regulations are most advanced at the national level in many countries and at the EU regional level. Further, there have been legal cases to establish the binding nature of those regulations. Thus, global, regional or local binding regulations are not likely to be instituted, or effective if they are developed. In contrast, in maritime shipping there are already binding emission regulations concerning the sulfur content of fuel in effect at the International Maritime Organization, with an agreement that they will be strengthened in January 2020. As for maritime BC emissions, studies in progress will

provide an analytic base for binding limits.

The history of the International Civil Aviation Organization is not so encouraging about the prospect for binding regulations. Aviation thus offers a test case of the value of voluntary initiatives. Although in general voluntary initiatives by industry leaders and/or NGOs can certainly create political pressures, it is not clear yet that firms – and their partner governments - that are central to the global aviation industry are going to adopt significant binding regulations on airplanes' emissions for the foreseeable future. Thus far, voluntary measures have left the industry facing emissions projections that far exceed present levels.

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Appendix A. Black Carbon Definitions and Metrics

Concerning BC's contributions to climate change, the cause-effect relationships are complex; there are both generic metric issues and BC-specific metric issues (Fuglestvedt et al., 2010). The generic issues reflect the fact that climate scientists typically measure the cumulative radiative effect of various forcing agents by watts per square meter (W/m^{-2}), often covering the period from circa 1750 before the industrial revolution to recent years (US EPA, 2012: 32). Although this is a useful metric for determining historically the relative contributions of climate forcers to present temperatures, it is not necessarily useful for policy purposes when the principal concern is the future. In the context of the present paper - where the focus is on modern modes of transport - the relative contributions in past centuries of motor vehicles, maritime vessels and airplanes are obviously not indicative of their current or prospective contributions. Thus, metrics for Global Warming Potential and Global Temperature Potential are used in the paper.

In addition to generic metric issues, there are BC-specific metric issues about BC's contribution to climate change: analyzing the effects of BC emissions on climate change is challenging because of the presence of organic carbon (OC) emissions as co-pollutants with BC emissions. A key determinant of the net warming/cooling impact of emissions is the ratio of BC to OC (IPCC, 2013). The ratio of BC to OC in diesel emissions has been estimated to be as high as 9:1 (Azzara, 2013, 2015). Mobile diesel engines' BC emissions have been specifically estimated to be about 75 percent of soot's total (US EPA, 2017). Diesel fuel's high BC/OC ratio is therefore a key factor justifying the treatment of diesel engines as significant net sources of global warming.

The formation of clouds from BC emissions poses additional challenges to the estimation of net warming impacts. It is common practice, therefore, to distinguish between BC's “direct effects,” which do not take into account cloud formation, and BC's “indirect effects,” which refer to cloud effects. For instance, BC's “direct effects” on Arctic surface temperature warming have been estimated to be 0.4 °C from BC in the atmosphere and 0.22 °C from BC on snow. These estimates, however, do not include “indirect effects” from cloud formation (AMAP, 2015: 96). “Total effects” - or “total net effects” - include both direct and indirect effects.

Despite these measurement challenges, it is nevertheless possible to estimate both the per unit warming impact of BC emissions and the total global warming impact of all BC emissions in order to establish the relative significance of BC as a global warming agent. Per unit comparisons with carbon dioxide are presented in the table below, where metrics for both Global Warming Potential (GWP) and Global Temperature Potential (GTP) are presented. GWP is the integrated value of the cumulative effects of one pulse of BC at a specific time over the indicated subsequent period of time (usually 20 years or 100 years). GWP thus cumulates the effects over a specified time period, but it does not include emissions after that period of time. GTP indicates the temperature for one selected year with no weight for years before or after the selected year (IPCC, 2013, Technical Summary: 58). GWP is more commonly used in the climate change literature, but there are examples of the use of GTP as well.

Estimates of BC's impacts by the Inter-governmental Panel on Climate Change (IPCC) - which of course have been based on more data and more studies over time through five IPCC cycles of assessing climate science - have generally become larger. The data in the table are based on the most recent IPCC estimates from Assessment Report 5 (IPCC, 2013). The table presents data for both 20-year and 100-year time horizons. Although 100 years has been a widely-used time horizon on the grounds that the average atmospheric lifetime of carbon dioxide is about 100 years, a horizon of 20 years is often used for short-lived carbon pollutants such as BC. The table also presents four different indicators for BC – from three separate studies, one of which includes the albedo effect of BC, which reduces snow and ice reflectivity. The most inclusive indicator, which is in the bottom row, shows an estimate of 2900 for BC GWP relative to carbon dioxide at 20 years. Despite issues about particular metrics, the basic patterns in the table are clear: BC's impact per tonne is much greater than carbon dioxide's, with an order of magnitude from tens (GTP-100 year) to thousands of times greater (GWP-20 year).

Global warming impact per unit of black carbon emissions compared with carbon dioxide (mean estimate and 95 percent confidence interval).

Sources and scope of emissions data	GWP 20 years	GWP 100 years	GTP 20 years	GTP 100 years
Bond et al. (2013): global	3200 (270–6200)	900 (100–1700)	920 (95–2400)	130 (5–340)
Collins et al. (2013): global	1600	460	470	64
Fuglestvedt et al. (2010): four regions[c]	1200 (+/−720)	345 (+/−207)	420 (+/−190)	56 (+/−25)
Bond et al. (2013): BC global – radiation + albedo	2900 (+/−1500)	830 (+/−440)	NA	NA

Source: Adapted from IPCC (2013: 740, Table 8.A.6). Also see Brewer (2015).

[a] GWP = Global Warming Potential.

[b] GTP = Global Temperature Potential.

[c] Regions: East Asia, European Union + North Africa, North America, South Asia. Includes aerosol-radiation interaction.

Appendix B. Technologies

Diesel particulate filters (DPFs) have been used on millions of motor vehicles in many countries for decades, and they have been found to be cost-

effective. The DPF issues concerning black carbon emissions are, therefore, mostly about the installation, standards, testing, monitoring and enforcement policies. These policy issues have, of course, been at the centre of the emissions testing scandals in the US and EU.

In maritime shipping, however, there are technological as well as policy issues about potential black carbon emissions reductions from particulate filters. Diesel particulate filters could reduce black carbon emissions by as much as 90 percent. It is important to note that lists of potential BC emission-reduction technologies and carbon dioxide emission-reduction technologies partially overlap but are not coterminous. Of course, this is not only a technical complexity, but it also poses a challenge to regulatory policy design and implementation. For analyses of shipping technological and operational measures to reduce *carbon dioxide* emissions, see Wan et al. (2018) and Eide et al. (2011).

In the aviation industry, because aviation fuel has a different emission profile compared with the diesel fuel used in motor vehicles and ships, the technological issues for reducing black carbon emissions are also different. Yet, there are also some fundamental similarities in the search for fuel efficiency and for alternative fuels. In the case of aviation, however, there are special challenges and opportunities (Hawken, 2017: 150–151). There are many opportunities for improved fuel efficiency, in both aircraft design and operations: Winglets can improve fuel efficiency by 5–7 percent depending on their precise design, but their uptake has varied among airlines (some planes of some airlines still do not have them). More opportunities exist in "placement of engines, fuselage width, width, length, and placement of wings …. " As for alternative fuels: "Jet biofuel options exist today, but cost is high, supply is limited, and infrastructure is poor." What about future uptakes and emission levels? There is a broad range of possibilities, including efficiency in the air, efficiency on the ground, building and construction, and many more. A US National Academies of Sciences (2015) Committee focused on propulsion and energy technologies with a 30-year horizon and an emphasis on carbon dioxide emissions. Most of their recommendations require large, long-term investments in R&D, with highly uncertain payoffs.

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